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Reconciling Agriculture with Biodiversity and Innovations in Plant Breeding

Agricultural intensification has boosted food production for many decades. However, at the same time, it has also led to a sharp decrease in agricultural diversity. Plant breeding has played a key role here. Today, a wealth of agro-genetic diversity – crops and their manifold varieties – is urgently needed in order to achieve global food security, and to adapt agriculture to a rapidly changing climate. This calls for sustainable biodiversity management involving new approaches to crop breeding.

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Plant breeding exists since crop domestication. For more than 10 000 years, farmers have been selecting plants that offer higher yields and are healthy. Uniformity in germination and ripening has also become important, as this allows for easier harvesting. Historically, plants were exposed and adapted to various environments such that gradually a rich, man-made crop diversity developed. Thousands of plant species were utilised, with each exhibiting significant diversity. In India, for instance, until a few decades ago, up to 30 000 rice cultivars were grown (Pretty 1995).

During the past 150 years, this trend in agricultural development has reversed. The biological diversity of crop plants has been dwindling. Today, only some 150 species are being cultivated, and no more than three of these (rice, maize, wheat) account for almost 60 percent of total global food production. Not only are fewer and fewer plant species being used for food and agriculture, but plant breeding and commercial seed production have also helped reduce genetic diversity within individual species. While the number of varieties of any given crop is constantly decreasing, crop varieties themselves are becoming more and more uniform (Vellvé 1992, Finckh 2007, Teklu and Hammer 2006).

In addition, plant genes can possess traits like resistance to diseases, drought tolerance, etc. Their loss, also called genetic erosion, is now receiving increasing attention, as it coincides with two global challenges: namely, the need to ensure global food security, and the need to adapt to climate-induced environmental change (Kotschi 2007). It is becoming clear that plant genetic resources are crucial for both. Thus, the need to reconcile agricultural intensification with the conservation of agro-genetic resources is emerging as a fundamental concern. Plant breeding and seed production play a key role in this endeavour; one which requires a new approach.

Intensification in Agriculture

In the 50 years from 1950 to 2000, global grain production almost tripled (Dyson 1999). This growth was primarily made possible through progress in plant breeding, the use of synthetic nitrogen fertilisers, and effective herbicides for weed control. In terms of plant breeding, for self-fertilising crops (e. g., wheat and rice), only the best plants were selected over many generations (pedigree line breeding). Meanwhile, for cross-pollinating crops, systematic inbreeding to obtain hybrid varieties became the predominant standard in the 20th century (Phillips and Wolfe 2005). In addition, breeders often used the same “elite material” for breeding over and over again. As a result, although different varieties may exist, genetic diversity within each crop species has become low.

Furthermore, the productivity increase was mainly achieved on fertile land, under optimal growing conditions, and to the benefit of only a small percentage of farmers. According to Pimbert (2008), there are roughly 1.3 billion farmers worldwide, the majority of which (96 percent) are smallholders using mostly little or no external inputs. In the 1980s, Francis (1986) estimated that 60 percent of all agricultural land could be classed as being “resource poor areas” with traditional agriculture. Even though this figure would be smaller today, this sector still contributes substantially to world food production and is fundamental to food security – and not just in rural areas.

According to Tilman et al. (2002), the world population is expected to grow by 50 percent to approximately nine billion peo-

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ple by 2050, and global grain demand for food purposes is expected to increase by 70 percent – due to both the increased number of people needing to be fed, and the rising proportion that changes its diet in favour of greater meat consumption. As the potential to expand the amount of agricultural land is limited, further intensification is required. However, it is highly debated how this can be achieved. Also, there is increasing evidence that it would be unsuitable to continue using present intensification strategies into the future (Kotschi 2009).[1] Instead, a new understanding of intensification is required; one that embraces the issue of sustainability and combines production with environmental targets. In other words: agriculture has to use nutrients and energy more efficiently, it must sustain ecosystems and their functions while conserving biodiversity, and it has to be climate-friendly.

Such agricultural intensification can best be achieved by focusing on the resource poor areas that have been neglected in the past. The factors of neglect are manifold and their underlying relationships complex. Markets are lacking. Suppliers of agricultural inputs and other service providers are largely absent, and there is a lack of appropriate technology, including crucial plant breeding. Thus, appropriate intensification measures must be applied in a setting where the initial yield level is not one of eight tonnes of grain per hectare (as under optimal growing conditions), but often of one tonne per hectare or less. Yield increases to even two, three, or four tonnes per hectare could boost food production greatly. If such measures were to be combined with crop diversification, i.e. the inclusion of a wider range of "minor" crops, food security could be improved significantly.

Modern crop varieties, however, are often inappropriate for the intensification of such areas. For the past century, breeding has focused on optimal agricultural environments where nutrients and water are in abundant supply. As a consequence, high-yielding varieties (HYV) mostly depend on inputs such as chemical fertilisers, synthetic pesticides and irrigation in order to be successful. But this means that they are unsuitable for the majority of farmers worldwide who are invariably fighting low soil fertility, seasonal droughts or other environmental constraints. Under the farming conditions experienced by them, modern crop varieties often perform poorly, making the use of fertilisers and agrochemicals uneconomical. Surging input costs only serve to aggravate the problem. This is a challenge that plant breeding has to address. Two innovations in plant breeding – evolutionary methods and participatory organisation – merit particular attention.

Local Varieties – a Source for Intensification

The search for alternatives started 50 years ago (Suneson 1956) and led to today's method of evolutionary plant breeding (Murphy et al. 2005). This method can be described as follows. In order to generate new varieties, breeders systematically utilise local varieties that are genetically diverse and have adapted ecologically (Phillips and Wolfe 2005) – landraces of different evolutionary origin are assembled and recombined through cross-pollination, with the resulting mixtures known as composite cross populations. Over several generations, the progenies are propagated as bulk, and the bulk is subjected to natural and artificial selection under various ecological conditions, finally resulting in a modern local variety. In many breeding experiments with barley (Suneson 1956) and with wheat (Qualset 1968, Thomas et al. 1991), composite cross varieties have been found superior to leading high-yielding commercial varieties because they perform better under various environmental conditions. It is now clearly evident that yield stability and achieving a high yield over a range of environments requires genetic diversity (Soliman and Allard 1991). Moreover, Murphy et al. (2005) conclude that natural selection favours genotypes that produce high yields in environments with fluctuating selection pressures (e.g., variation in temperature or rainfall) – a feature of most agro-ecosystems.

Another important fact is that composite cross populations have better disease resistance. Increasing genetic diversity not only helps limit disease-induced yield reductions (Wolfe 1985, Garrett and Mundt 1999, Zhu et al. 2000), but genetically diverse populations also adapt well to changing disease patterns (Allard 1990). The co-evolution of plants and diseases in genetically diverse populations is an effective, self-regulating mechanism that maintains the disease resistance of a plant. This is a characteristic which is generally not found in genetically homogeneous crops (Murphy et al. 2005).

Therefore, evolutionary breeding with composite cross populations has become a very promising method for intensification of land use and for future adaptation of crops to environmental change. This applies, in particular, to agriculture in areas where environmental conditions are marginal and may, in times of climate change, become highly relevant to farming in general. And breeding programmes for organic agriculture are increasingly applying this method (Finckh 2007).

Breeding with Farmers – Sometimes Faster and More Efficient

Another innovation of note is participatory plant breeding (PPB). Contrary to classical approaches, breeding is not done by breeders alone. Instead, farmers are fully involved throughout the entire breeding process – from the planning stage to the testing of cultivars.

Furthermore, breeding mainly takes place in farmers' fields, and not in research stations. In this way, any bias can be avoided. This point is important, as research stations typically have better soils, possibly irrigation facilities, etc., whereas farmers' fields offer a full range of environmental (and management) conditions for cropping – hence there is optimal interaction between environment and genotype during the breeding process.

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1 For details see International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD): *www.agassessment.org*.

An example of PPB is presented by Ceccarelli (2006), who breeds barley in Syria (figure 1). Crosses from bulk collections and the following two generations (F1 and F2) are undertaken on-station and by breeders. Then testing is carried out on farmers' fields over a period of three years in "initial", "advanced", and "elite" trials. Once this stage has been completed, either the material is released as a variety or the whole process is repeated.

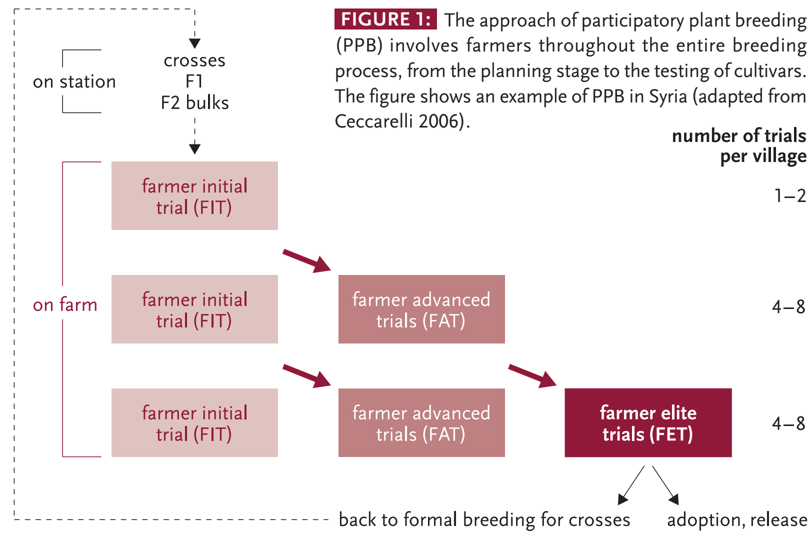

FIGURE 1: The approach of participatory plant breeding (PPB) involves farmers throughout the entire breeding process, from the planning stage to the testing of cultivars. The figure shows an example of PPB in Syria (adapted from Ceccarelli 2006).

PPB emerged during the past ten years. It has mainly been promoted by international research centres, such as ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) and ICARDA (International Center for Agricultural Research in the Dry Areas), and non-governmental organisations, such as Masipag in the Philippines (Bachmann et al. 2009) and Kultursaat in Germany. This process is now being practised in developing countries around the world, and with outstanding results in three particular regions. Namely, as regards barley in the Middle East (Ceccarelli 2006), rice in South Asia (Witcombe et al. 1996), and sorghum in West Africa (Weltzien et al. 2006). In all three areas, improving drought-tolerant cereals in low rainfall environments has been a primary objective. The method has now been extended to other crops, vegetables and maize (Sunvar et al. 2006, Visser et al. 2006, Song and Jiggins 2003).

Given its impact, there are at least three strong arguments in favour of PPB:

- The effectiveness of breeding can be improved as farmers' experiences, agronomic knowledge and preferences are taken into account in the entire breeding process. All this gives varieties bred by this method high acceptance and accelerated adoption rates, contributing to a demand-driven approach to breeding (Ceccarelli and Grando 2007).
- Research efficiency can be improved. For instance, Ceccarelli (2000) has found that varieties selected by farmers are as high-yielding as those selected by breeders.
- The breeding time can be reduced. As on-farm testing is involved, the release of superior bulks requires only half the time usually needed. If pure lines are necessary, three to four years can still be saved (Ceccarelli 2006). This is an important aspect given climate change and the necessity of rapid adaptation.

Synergies of Both Innovations

Evolutionary and participatory plant breeding are intertwined. Together they form a new approach that represents an important complement to classical plant breeding. These innovations combine several advantages. Firstly, the seeds produced are more farmer-(or client-)oriented. Secondly, they have a higher resilience to varying environmental situations. Last but not least, farmers have the opportunity to select those materials most appropriate for meeting their requirements, and they can play a key role in the breeding process (figure 2).

The evolutionary and participatory plant breeding approach is still in the early stages of dissemination, but has a great potential for contributing to future agricultural development. It has already made a significant impact:

- ***Scientifically,*** the approach has broadened our understanding of appropriate breeding technologies. Complementing formal breeding, the new approach offers a methodology that focuses on crop-environment interactions and uses it systematically. This has stimulated discussion on genotype x-environment interaction and the new method that allows for breeding locally, under varying environmental conditions. Besides, breeders are becoming aware that breeding primarily for yield does not necessarily guarantee broad seed adoption by farmers. Therefore, more and more breeders are integrating farmer participation into their formal programmes.
- ***Socially,*** the approach helps to empower farmers to regain control of their seed systems, and to safeguard their interests after decades of marginalisation due to trade liberalisation. Small-scale farmers in marginal areas are now benefiting from agricultural research and development, as well as the recognition that greater efforts must be made to develop technologies better suited to improving their livelihoods (Almekinders and Hardon 2006).
- ***Economically,*** the approach answers the question of how to tap into the potential of marginal areas and to make a large range of minor crops more productive. This is one key aspect of the challenge to increase global food production.
- ***Ecologically,*** this new approach offers a solution to the problem of sustaining the diversity of agro-genetic resources and of developing these further in accordance with environmental change – and within a relatively short period of time. It also represents a response to the challenge of adapting fast to difficult and changing environments.

Scaling Up – Constraints to Overcome

For scaling up and making the new approach an institutionalised part of seed production, serious bottlenecks have to be overcome.

First of all, this requires a change of attitude among scientists, professionals, and political decision-makers, i. e. an attitude that acknowledges the value of and realises the need for the new approach. Only then can research policies be changed and national agricultural research centres moved to take up this approach.

Secondly, the process of privatising plant genetic resources has to be stopped. Growing corporate control over genetic resources and a monopolised seed supply are a serious constraint (Kotschi 2008). Instead, a substantial increase in public investment into this type of plant breeding is necessary, and the public sector has to regain control over the development of crop varieties.

Thirdly, national seed laws need to be amended. Today, only registered varieties can be distributed and traded in almost all countries. The registration criteria and procedures implemented exclude local varieties, as these do not meet high standards of distinctiveness, uniformity, and stability (DUS standards). Therefore, legal amendments have to be made that exempt local varieties and populations and allow registration at a much lower level and at less cost. Such a change however, is firmly opposed by the formal seed sector.

Finally, the role of different stakeholders in the seed sector has to be re-defined. Breeding and seed supply should be separated institutionally. Breeding should return into the public domain, whereas seed production and distribution is an entrepreneurial task for the private sector. The latter requires new business concepts, allowing for the systematic involvement of seed companies at a local or regional level.

Plant breeding and seed production cannot be considered in isolation. Both are components of rural development. They will only have a significant impact on food security and biodiversity conservation if agricultural smallholders gain access to resources (land, water, and other agricultural inputs) and markets, and if they can rely on improved transport infrastructure and reasonable commodity prices. In this context, the key requirements for the seed sector are:

- The topic of seed supply – breeding, production, and marketing – must be put back on the agenda of rural development.

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FIGURE 2: Farmers in the Philippines are breeding local rice varieties. Many of them return to farm-saved seed.

- Public funding for plant breeding has to be increased substantially.
- The amendment of seed laws must be given priority in the advisory services provided to governments.
- The importance of plant genetic resources in adapting agriculture to climate change needs to be understood and incorporated into national development plans, programmes, and projects. The same goes for agricultural research and rural development.
- The private and public sectors must collaborate in the provision of suitable seed.

The ongoing paradigm change in agriculture towards sustainable intensification must embrace the role of agro-biodiversity in general, and the need for innovation in plant breeding in particular. Evolutionary, participatory plant breeding has the potential to contribute significantly to agriculture in the future.

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